

# Brief reply to “Can gravity account for the emergence of classicality?”

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In a series of comments, Bonder et al. criticized our work on decoherence due to time dilation [1]. First the authors erroneously claimed that our results contradict the equivalence principle [2], only to “resolve” the alleged conflict in a second note [3]. The resolution – relativity of simultaneity – was already explained in our reply [4], which Bonder et al. now essentially reiterate. The newly raised points were also already extensively clarified in our note. The physical prediction of our work remains valid: systems with internal dynamics decohere if the superposed paths have different proper times.

In a recent note, Bonder et al. “resolve an apparent conflict between [our] results and the equivalence principle” [3]. This apparent conflict was introduced by the same authors in their previous comment<sup>1</sup> claiming that our results “cannot be right in light of the *equivalence principle* [because] the situations of interest can be analyzed in a free falling frame [and] such scenarios cannot lead to decoherence, as, without gravity, there is nothing to cause it” [2]. The claim is quite surprising considering that the effect we describe only depends on proper time and rest energy, which are coordinate-independent and quite compatible with the equivalence principle. Indeed, the claim is incorrect. As Bonder et al. realize in their new note, what they interpreted as different reference frames “are not describing the same physical situation from two perspectives, but two different situations” [3]. This precise point was extensively discussed in our answer to their concerns, sections IIIA-D of ref. [4]: “different observers will use different planes of simultaneity and thus will assign different states, simply because they are describing *different physical situations*”<sup>2</sup>. What is important, however, is that once a physical situation is specified (e.g. an interference experiment), different reference frames give the same prediction, namely the one given in our work.

Bonder et al. further “emphasize that predictions regarding the observability of interference become relevant only in the context of concrete experimental settings” [3]. Indeed, we treat coherence as a physical property that is revealed in interference experiments, as emphasized throughout our works (for example in fig. 2 in [1], see also ref. [5]). As interfering paths have common initial and final points, no ambiguity related to the choice of equal-time surface arises.

Thus, despite the critical tone, in their most recent note Bonder et al. use our same explanations and reiterate the central prediction of our work: systems with internal dynamics decohere if the superposed paths have different proper times. A few points of confusion remain by Bonder et al., which we already resolved in ref. [4]. First, in the use of the word “universal”: As explained in our works, it means that time dilation affects all composite systems, not that the effect is inevitable. Second, in the role of decoherence: As commonly understood in the literature, it suppresses quantum effects in experiments, which thus appear classical for all practical purposes, it does not turn quantum states into “proper mixtures”. Third, in the mass superselection rule: it has no relevance for our work, as we are discussing relativistic effects. Finally, Bonder et al. question in which sense gravitation is related to the effect: it is in providing the gravitational time dilation responsible for decoherence, as the title of our work suggests. These and further concepts underlying our work are discussed in ref. [4].

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[1] Pikovski, I., Zych, M., Costa, F., & Brukner, Č. *Nature Physics* **11**, 668-672 (2015).

[2] Bonder, Y., Okon, E., & Sudarsky, D. arXiv:1507.05320 [quant-ph] (2015).

[3] Bonder, Y., Okon, E., & Sudarsky, D. arXiv:1509.04363 [gr-qc] (2015).

[4] Pikovski, I., Zych, M., Costa, F., & Brukner, Č. arXiv:1508.03296 [quant-ph] (2015).

[5] Zych, M., Costa, F., Pikovski, I. & Brukner, Č. *Nat. Commun.* **2**, 505 (2011).

<sup>1</sup> The second arxiv version of this comment is quite different from the first one to which our reply [4] referred. It also differs from the one submitted to Nature Physics. All versions state that our results contradict the equivalence principle.

<sup>2</sup> The similarity between their figure 4 in [3] and our figure 1 in [4] is also quite evident, although these kind of figures and discussions are found in any exposition on basic relativity.